Technology Innovation:
Highly Flexible Storage Heat Pump (HFSHP)

The findings will be relevant to the heat pump industry, specifically designers, manufacturers, installers. It will also be relevant to utility companies.

Project lead:

Kensa Heat Pumps Limited

Partners:

The Manufacturing Technology Centre Ltd (MTC)

The Power Networks Demonstration Centre (PNDC), The University of Strathclyde

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What were the objectives of the project?

By incorporating smart control systems, the technology will support demand-side response and help address grid strain concerns as heat pump adoption scales up. The project's core aim was to develop the Highly Flexible Storage Heat Pump (HFSHP) to satisfy heating and hot water loads while directly integrating chemical thermal storage for improved flexibility and efficiency.

The main objectives were the following:

1) **Developing the HFSHP, including phase change material (PCM) integration and testing:** build on Kensa's previous work on the PCM integrated heat pump unit, which has already reached Technology Readiness Level 6 (TRL6 – technology model or prototype demonstration in a relevant environment) by integrating thermal heat stores into heat pumps. Kensa's vision was to disrupt the heat pump market by introducing the HFSHP to a broad customer base. Achieving this vision required developing two distinct product variants: an internal and external unit, both

tailored to different sizes, locations, and refrigeration circuit configurations. Kensa prioritised designing both variants with similar assembly, installation, and maintenance processes to ensure market adoption and cost-efficiency. This strategic approach aimed to minimise business spending on new manufacturing infrastructure while keeping costs competitive to attract a wider range of customers.

2) **Developing and testing an optimised controls strategy:** develop and commission advanced smart control systems capable of optimising load-shifting and integrating with future demand-side response technologies.
3) **Performance validation and network testing:** validate performance and demonstrate the HFSHP's ability to reduce peak load impacts on the electrical grid by enabling demand-side response, grid balancing, and use of low-carbon electricity during off-peak periods.

What activities were funded?

Kensa's activities for the project focused on developing and testing the HFSHP. Key technical work involved designing a heat pump compatible with thermal storage by trialling components to improve efficiency and temperature consistency. Efficiency testing ensured compliance with industry standards while incorporating innovations in thermal storage. Developing a control system prototype enabled load-shifting management while cross-platform integration focused on managing charge levels of thermal stores and creating a smart thermostat.

The Manufacturing Technology Centre (MTC) contributed by enhancing product design and manufacturing efficiency. Initial activities involved benchmarking the product and capturing requirements, followed by concept design work in collaboration with Kensa to integrate thermal storage. Subsequent phases included detailed design and prototype manufacturing to support testing and refinement. MTC also worked on establishing a sustainable supply chain to enable large-scale production using UK-based suppliers.

The Power Networks Demonstration Centre (PNDC) evaluated the HFSHP's integration into the electrical grid. Modelling and scenario analysis compared the new prototype to standard heat pumps across various home types and demand scenarios. High-resolution models were developed to understand performance and energy use in different contexts. Hardware-in-loop testing used PNDC facilities to simulate real-world conditions and assess the HFSHP's impact on the distribution network, particularly during winter and peak demand periods, ensuring the technology supported grid stability and demand-side response.

What did the project achieve?

The project successfully developed a prototype design for the internal HFSHP and is progressing towards developing a working prototype for the external unit. Reaching these stages involved selecting and testing refrigerants for both units. Refrigerant legislation in the UK is changing, with increasing restrictions on the use of high Global Warming Potential (GWP) refrigerants. The external unit was designed to be compatible with low-GWP refrigerants, and the team plans to refine the internal unit's product design to ensure compatibility with low-GWP refrigerants in anticipation of legislative changes. PCM integration was also a key part of the design process, enabling the heat pump system to act as a thermal store. The project team developed prototype designs for the system integrating 58°C Sunamp PCM units, which offers the benefit of compatibility with the higher flow temperatures encountered frequently in retrofit scenarios.

Optimised control strategies were tested and developed for the HFSHP units with the aim of maximising energy efficiency and reducing energy costs. The project devised an optimisation calculation to simulate the thermal dynamics of the house, including the heat pump and PCM thermal store. Smart controls were developed based on this model. The project team then conducted annual energy forecast simulations for various household types and conditions to evaluate the performance of the thermal store and the energy cost savings achievable through control optimisation. The results showed that the optimised control strategy could reduce annual space heating costs by 20% under certain time-of-use tariffs, with the greatest savings achieved for smaller and better-insulated properties.

Performance validation and network testing were carried out to validate that HFSHPs could provide demand-side flexibility through thermal storage and operate reliably within the distribution network by load-shifting. One confirmed benefit of the network is the potential to reduce transformer loading and voltage drop. This could lead to increased heat pump adoption beyond what is possible within current infrastructure limits. Testing the prototype unit demonstrated that the HFSHP could match the performance of standard heat pump systems under various real-world scenarios; however, the PCM thermal storage performed best at lower flow temperatures and loads. The HFSHP system's ability to deliver cost-saving benefits to consumers and alleviate electricity network constraints depends on the smart controller implementing effective load-shifting strategies.

Project objective 1: Developing the HFSHP, including PCM integration and testing

Why is this important?

Developing a Highly Flexible Storage Heat Pump (HFSHP) with integrated phase change material (PCM) offers several key benefits. The incorporation of PCM enables effective thermal energy storage and load-shifting, allowing heat pumps to operate efficiently during off-peak hours and supply stored heat during periods of high demand. This reduces pressure on the electrical grid and maximises the use of low-carbon electricity, supporting national carbon reduction targets.

The HFSHP's innovative design boosts system efficiency by capturing excess heat generated during the superheat stage of the refrigeration cycle—heat that would otherwise be wasted. This recovered energy is repurposed to produce domestic hot water (DHW) as a by-product of space heating, improving charging performance by approximately 7% for space heating and approximately 21% for hot water provision, lowering operational costs for users.

The HFSHP provides a scalable, sustainable solution for new builds and retrofit projects. By addressing critical challenges in energy efficiency, cost reduction, and carbon emissions, the HFSHP with integrated PCM represents a significant technological advancement, promoting a cleaner and more sustainable energy future.

What activities were funded?

The activities funded related to developing the HFSHP and PCM integration include:

- Selection and testing of the refrigerant component: suitable refrigerants were identified and tested for internal and external HFSHP units.

- PCM specification and optimisation: the PCM's specifications were identified and optimised to ensure it met the HFSHP's thermal storage and efficiency requirements.
- Heat exchanger design: the heat transfer efficiency between the PCM and the heating system was maximised by developing and testing the heat exchanger's geometry.
- Charge measurement: precise charge measurement techniques were implemented to monitor the PCM's state of charge, which is crucial for maintaining the HFSHP's efficiency and functionality.
- Prototyping and testing: the project team built and tested prototypes to validate the PCM integration's performance, including its ability to store and release heat effectively.

These activities aimed to enhance the efficiency, manufacturability, and market readiness of the HFSHP with integrated PCM.

What were the project findings, and did the project achieve this objective?

This phase aimed to achieve efficient superheat recovery by integrating PCM heat storage to improve overall performance. The project focused on developing a PCM-integrated refrigeration circuit design concept to manage charge levels between PCMs and avoid overheating.

The Internal HFSHP variant reached a prototype design stage, which was designed for delivery in two units (Top and Bottom) due to weight constraints. The HFSHP internal product variant component diagram is shown in Figure 1.

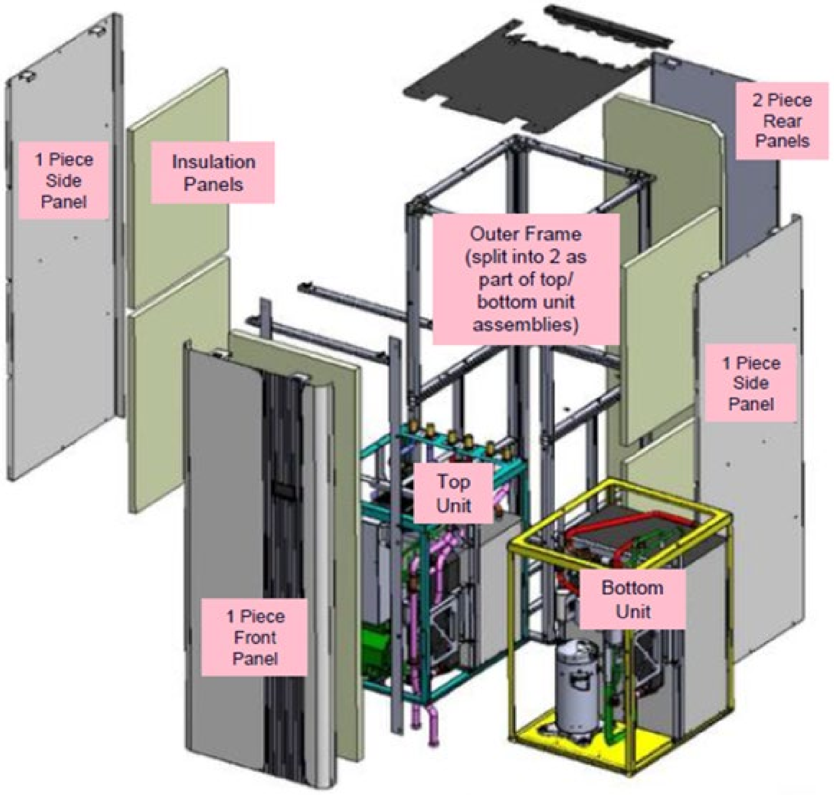

Figure 1: HFSHP Internal product variant

The Manufacturing Technology Centre (MTC) also designed an external HFSHP variant to support low-GWP refrigerants, as shown in Figure 2. Key outputs included design verification through manufacturer specifications and simulations, a Bill of Materials for prototype construction, a rendered animation for assembly guidance, and iterative design reviews with Kensa to incorporate feedback. Kensa's next steps involved defining internal components and heat pump schematics to progress toward creating a working prototype.

Figure 2: HFSHP External product variant

The initially developed HFSHP unit used excess discharge superheat to simultaneously store heat for space heating and domestic hot water (DHW) in two Sunamp PCM units (48°C and 58°C) connected in series, aiming to deliver a higher CoP (Coefficient of Performance) and enable load-shifting. Due to specific PCM product withdrawals in the market, the project is now exclusively working with 58°C PCMs [1]due to the unavailability of a market-ready 48°C material. Using 58°C PCMs de-risks the project and offers a commercially advantageous product with higher flow temperatures, making it more suitable for retrofit scenarios.

Project objective 2: Developing and testing an optimised controls strategy

Why is this important?

Developing and testing an optimised control strategy for the HFSHP is crucial for maximising the system's efficiency and performance. An optimised control strategy ensures that the heat pump operates at its highest efficiency by intelligently managing the integration of PCM and the heat pump's various components. This includes precise control over the charging and discharging cycles of the PCM, which is essential for effective load-shifting and thermal storage. By optimising these controls, the system can better respond to varying energy demands and grid conditions, reducing operational costs and enhancing the overall reliability and lifespan of the heat pump. An optimised control strategy also

[1] A 58°C Phase Change Material (PCM) refers to a substance that changes its phase (usually from solid to liquid and vice versa) at 58 degrees Celsius.

facilitates seamless integration with smart home energy management systems, enabling users to take full advantage of time-of-use tariffs and other demand response programs. This provides consumer cost savings and supports grid stability and the broader adoption of renewable energy sources.

What activities were funded?

The main activities related to the development of optimised control strategies for the HFSHP included:

- Product controls development: creating a new system manager for heat pump technologies, ensuring integration with smart thermostats and home energy management systems. Central to these was the development of optimisation calculations, which included the ability to model the heat pump with the integrated PCM. This calculation was used to run annual forecast simulations over a year to explore the benefits of the thermal store under various scenarios, such as time of use tariffs, house types, and discharge characteristics.
- Cross-platform integration: ensuring compatibility with smart thermostats and energy suppliers to facilitate load-shifting and tariff optimisation.
- Control logic and protocols: developing control logic and communication protocols to enable the HFSHP to interact effectively with smart home systems and the electrical grid.
- Testing and validation: conduct extensive testing to validate the performance and reliability of the optimised control strategies in real-world scenarios.

These activities aimed to enhance the efficiency, flexibility, and user-friendliness of the HFSHP through advanced control mechanisms.

What were the project findings, and did the project achieve its objective?

Smart controls were based on an optimisation calculation that represented the thermal dynamics of the house using a “thermal block model” with thermal conduction between elements like radiators and rooms. The approach involved adding the PCM thermal store as an additional thermal block between the heat pump and the radiators, with conduction to the radiators depending on the discharge speed. The discharge power was mapped to a controllable working variable, which was constrained by the temperature difference between the thermal store and the radiators. This resulted in a linear model that allowed the system to be optimised. This power was then mapped to the discharge flow rate, with the maximum pump speed being a key characteristic. Although this approach approximated the non-linear PCM behaviour and direct refrigerant coupling, the optimisation still managed the key trade-offs in the system.

The annual forecasting tool predicted the performance of energy assets in homes over a year at half-hourly intervals. Each simulation used a digital twin of a house, with randomised thermal dynamics and a heat transfer coefficient consistent with the house type, size, and insulation level. The householder could specify the heating schedule and setpoints. The method assumed that smart controls were in place, providing coordinated optimisation of all assets. Load profiles and running costs were predicted for different heating system options and low-carbon technology configurations.

The simulations showed that incorporating the thermal store alongside the optimised control strategy could significantly reduce annual space heating costs, depending on the time-of-use (ToU) tariff used. When using the Octopus Intelligent Go tariff, adding a thermal store resulted in up to 20% savings compared to an optimised system without a thermal store. Similarly, with the Octopus Cosy tariff—

designed for customers with air or ground-source heat pumps—the addition of a thermal store led to an 8% reduction in heating costs.

The thermal store benefited from charging at times with cheap rates and discharging later to avoid peak rate consumption. The optimised control strategy also leveraged thermal storage within the building fabric and the dedicated thermal store, with the balance depending on the rate of room cooling.

There was a trade-off with the reduction in the CoP due to the heat pump warming the thermal store to a higher temperature than the radiators. This effect might be less significant due to the direct refrigerant coupling with the HFSHP. The ratio of heat demand to thermal storage capacity determined the level of savings, with more benefit for smaller or better-insulated properties.

Going beyond the project timescale, the next step will be integrating the thermal store optimisation within the Smart Thermostat and implementing a controller that dictates the charge and discharge of the thermal store in real time.

Project objective 3: Performance validation and network testing

Why is this important?

Performance validation and network testing are essential to ensure the HFSHP operates effectively, reliably, and sustainably under varying conditions.

Validating the HFSHP's demand-side flexibility ensures the system can store thermal energy during periods of low demand and release it during peak times. This helps reduce strain on the electrical grid, enhance grid stability, and maximise the use of renewable energy, thereby lowering carbon emissions. Demand-side flexibility testing also identifies potential consumer cost savings through time-of-use tariffs and other demand response programs. Ensuring reliable performance under different scenarios is critical for widespread technology adoption and achieving national energy efficiency and sustainability goals.

In collaboration with the Power Networks Demonstration Centre (PNDC), network testing assesses the HFSHP’s ability to manage and shift loads effectively. Testing in a realistic distribution network environment validates its performance under various scenarios, ensuring robustness and regulatory compliance. This process optimises energy efficiency, minimises operational costs, and helps plan for large-scale deployment without causing disruptions. These activities are critical for demonstrating the practical benefits and scalability of the HFSHP, supporting its contribution to a sustainable and efficient energy system.

What activities were funded?

The key activities funded to undertake performance validation and network testing were:

- Heating Hardware-In-the-Loop (HHIL) test system: creating a test system that integrated the Internal Variant HFSHP prototype and Kensa's test rig with a simulation environment using Simulink housing models and a MATLAB control script. This setup enabled comprehensive testing and optimisation under realistic conditions. A schematic diagram is shown in Figure 3.

- Network testing and modelling: modelling and assessing the HFSHP's impact on the distribution network. The project aimed to ensure that the system could operate reliably and efficiently within grid constraints by evaluating its load-shifting capabilities.

What were the project findings, and did the project achieve its objective?

Several tests were conducted to validate the functionality of the HHIL interface, focusing on the ability of the MATLAB/Simulink simulation environment to control the test rig and HFSHP prototype. These tests were developed and verified collaboratively with Kensa staff on-site.

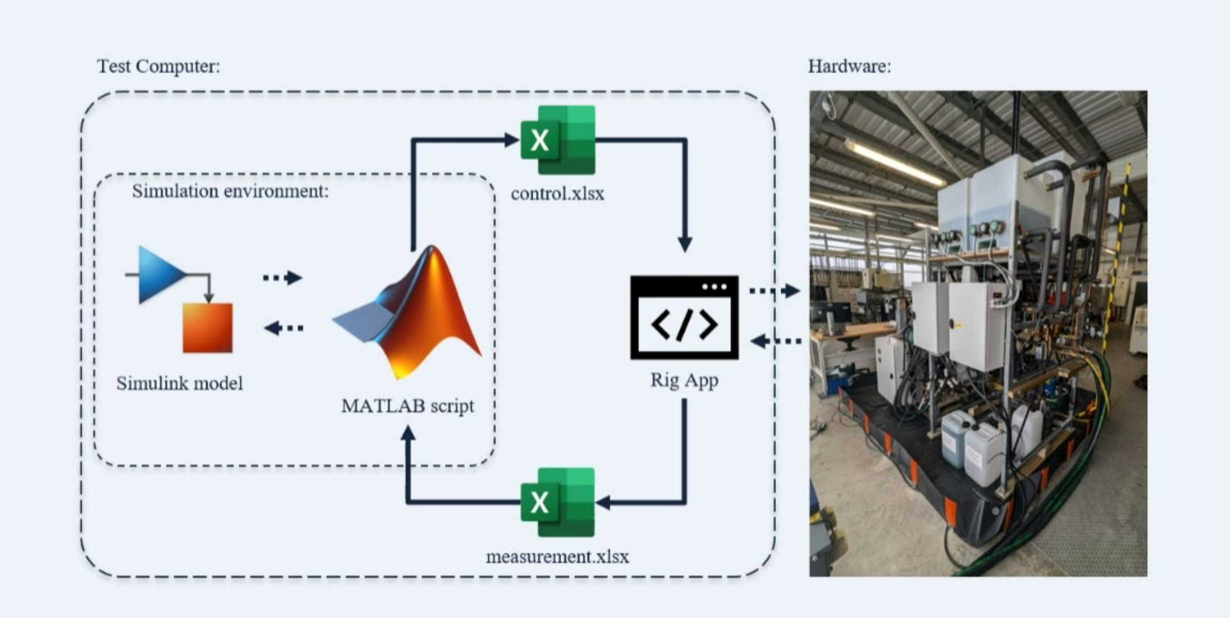

Figure 3: Heating Hardware-In-the-Loop (HHIL) Test System schematic diagram

The test rig and HFSHP prototype demonstrated the ability to replicate standard heat pump system base case results accurately. Although the buffering effect of building fabric largely evened out differences in internal building temperatures, variations in heat supply profiles were observed due to adaptive control of the HFSHP flow temperature and test rig return temperature. These differences are expected to be less pronounced in a commercially available HFSHP. Nine test cases were developed to assess the performance of the HFSHP prototype system. The cases represented three housing archetypes across different points in the heating season to test the performance in various scenarios.

Testing the HFSHP prototype demonstrated the ability to shift loads between 34 minutes and 3 hours, with the greatest durations at lower flow temperatures and loads. A greater load-shifting duration means that the thermal store discharges for a longer period during peak demand, reducing the strain on the network and minimising the need to purchase electricity at the highest tariff rates. Higher flow temperatures deplete the PCM storage capacity faster, making the HFSHP more effective for homes with lower flow temperature requirements, particularly at the start or end of the heating season. Additionally, a drop in PCM temperature before the phase change indicated that the HFSHP may not be suitable for flow temperatures of 55°C or higher. However, this issue could be mitigated by limiting flow temperatures or altering the PCM specification. The testing results also demonstrated that the compressor could recharge the PCM after the store had been discharged, but constant setpoint temperature control constrained load-shifting potential.

Overall, the best results for the HFSHP system were achieved at lower flow temperatures and loads. While the HFSHP can replicate conventional heat pump operations across various real-world scenarios, its success in delivering benefits to consumers and electricity networks hinges on effective load-shifting strategies implemented by the smart controller. The system could reduce energy bills for consumers by using variable tariffs to charge the thermal store at times of low network demand when tariffs are low, and discharge during periods of peak demand when tariffs are highest. Local network constraints can also be alleviated by implementing smart controls to load-shift to lower peak demand.

Implementing HFSHPs has the potential to reduce transformer loading and voltage drop for the network operator, enabling increased heat pump adoption beyond what is possible within current infrastructure limits.

Summary

What impact will this have?

The Highly Flexible Storage Heat Pump (HFSHP) project proposes several significant impacts on the UK, including reducing national carbon emissions by enabling efficient load-shifting and using low-carbon electricity, supporting the UK's Net Zero targets. It enhances grid stability by storing and releasing thermal energy during peak and off-peak times respectively, reducing strain on the electrical grid and minimising the need for costly infrastructure upgrades. The project aims to lower operational and installation costs for heat pump systems, making them more affordable for consumers and promoting wider adoption. Integrating Phase Change Material (PCM) improves overall efficiency, leading to significant energy savings. By reducing heating costs, the HFSHP has the potential to help alleviate fuel poverty.

What's next?

The next stage of the project will involve preparing for market launch and developing strategies for widespread adoption of the HFSHP system. This includes engaging with industry stakeholders and potential customers.

Where to find out more

https://www.kensaheatpumps.com/

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